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Liquid air/nitrogen energy storage and power generation system for micro-grid applications

Khalil M. Khalil [a], [b], *, Abdalqader Ahmad [a], S. Mahmoud [a], R.K. Al-Dadah [a]

[a] *The University of Birmingham, The Department of Mechanical Engineering in the School of Engineering, Birmingham B15-2TT, UK*
[b] *The University of Baghdad, Mech. Eng. Dept., Iraq*

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ABSTRACT

The large increase in population growth, energy demand, CO_2 emissions and the depletion of the fossil fuels pose a threat to the global energy security problem and present many challenges to the energy industry. This requires the development of efficient and cost-effective solutions like the development of micro-grid networks integrated with energy storage technologies to address the intermittency of renewable energy sources, provide localized electricity production, and smooth out power demand and supply curve. Among other energy storage systems, the cryogenic energy storage (CES) technology offers the advantages of relatively large volumetric energy density and ease of storage. This paper concerns the thermodynamic modeling and parametric analysis of a novel power cycle that integrates air liquefaction plant, cryogen storage systems and a combined direct expansion with closed Rankine power recovery system using two cryogens, liquid nitrogen, and liquid air. This cycle is part of a micro-grid system that provides electricity for a typical 50 unit residential building using either renewable energy sources or national grid off-peak electricity. This power cycle was modeled using MATLAB integrated with REFPROP software to investigate its performance at various operating conditions. Results showed that using liquid air as the working cryogen can significantly improve the cycle performance compared to that of liquid Nitrogen at all operating conditions, yielding maximum round trip efficiencies of 63.27% and 84.15% respectively. Also results showed that as the cryo-turbine efficiency and recovery expansion ratio are increasing the cycle round trip efficiency and network will increase, while as the compressor efficiency increases the round trip efficiency increases and the network decreases to reach the best value at 84% to produce round trip efficiency 80.62% and work 397 kJ/kg for the liquid air condition.

1. Introduction

The continuous growth in population and urbanization levels have increased energy consumption, CO2 emissions, the demand-supply mismatch and present major challenges to the energy industry (Sandoval et al., 2017). This requires the development of novel solutions that optimize energy use and minimize fuel consumption and emissions (Di Somma et al., 2015). Residential buildings are responsible for a significant proportion (approximately 30%) of the global energy consumption and carbon emissions due to a large number of populations living in them (McKenna et al., 2017). Therefore, the ability to control the timing and levels of electricity consumption in buildings will have a significant impact on the electricity demand-production profile and plays a major role in developing sustainable energy strategies (Marino et al., 2013). Recently, there has been considerable interest in microgrids (MGs) for various buildings like residential, commercial and industrial as an attractive solution to local efficient energy generation, reduce carbon emissions and national grid losses (Lidula and Rajapakse, 2011). A microgrid is a local system to generate, store and provide energy for buildings as a standalone system or connected to the main utility grid, using wind turbines, fuel cells, photovoltaic panels, diesel generator, and microturbines for power generation (Chan et al., 2017). MGs are flexible, smart and active power systems that able to improve the national grid efficiency and security, thus allowing more integration of renewable energy sources (RESs) (Elsied et al., 2016). With the increased integration of renewable energy sources in micro-grids networks, there is a need for effective solutions to manage the time shift between energy production and

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* Corresponding author. The University of Birmingham, the Department of Mechanical Engineering in the School of Engineering, Birmingham B15-2TT, UK.
E-mail address: Khalil3alani@gmail.com (K.M. Khalil).

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demands (Vieira et al., 2017). Although load shifting has been proposed as a mean to adjust power demands in buildings and reduce peak electricity load, like using water heaters, refrigerators and washing machines, however, not every type of power demand is suitable for load shifting, including lighting and cooking (Ding and Hong, 2013).

Energy storage (ES) offers the ability to manage the surplus energy production from intermittent renewable energy sources and national grid off-peak electricity with the fluctuation of electricity demand and provide the required flexibility for efficient and stable energy network (Stinner et al., 2016). The main storage technologies are mechanical, electrical, chemical and thermal energy storage technologies, detail description and comparison of these storage technologies in terms of system energy density, the efficiency of recovery, development level, capital cost, advantages, and disadvantages are presented in (Luo et al., 2015). Currently, the large-scale energy storage plants with a storage capacity of 100 MWh used worldwide are Pumped Storage Hydropower (PSH) and Compressed Air Energy Storage (CAES) (Hameer and Niekerk, 2015). The PSH is a mature storage technology which makes 95 GW of the worldwide storage capacity, while the CAES technology is growing, for example, the McIntosh site in Alabama generates 226 MW of electricity using CAES technology (Dodds and Garvey, 2016). Both PSH and CAES suffer from drawbacks in terms of geographical restrictions, high capital costs, environmental impacts and limited potentials for future development (Mahlia et al., 2014). Cryogenic energy storage (CES) technology offers the advantages of relatively large volumetric energy density, ease of storage and offers the potential to overcome the PSH and CAES drawbacks (Abdo et al., 2015). Also, this system is economically viable due to the relatively low capital cost (3–30 $/kW h) (Chen et al., 2009). Cryogens normally refer to a liquid media (liquefied gasses) that boils at temperatures below −150 °C such as liquefied natural gas (LNG), liquid air (Lair) and liquid nitrogen (LN2) (Li et al., 2010a). The use of cryogen as an energy carrier in energy storage system is more efficient than other energy carriers since the energy is stored through decreasing the internal energy while increasing the exergy of the cryogen (Chen et al., 2009). Despite the high energy density, safety, availability and very low environmental impacts, the use of liquid air/nitrogen as an energy carrier has not been extensively exploited (Li et al., 2010b). Recently, increased interest in liquid air energy storage technology (LAES) for grid scale application has been reported and few pilot plants are developed such as (Sciacovelli et al., 2017) which used packed beds to improve efficiency of LAES by 50% and (Chen et al., 2016) worked with optimum pressure of the working fluid 20 MPa to achieve an overall efficiency of 50% using a waste heat source.

With the increased interest in cryogenic energy storage, there is a need to develop efficient energy recovery technologies that exploit the cryogen stored energy. Several studies were carried out investigating the use of combined cycles using a range of working fluids, as summarized in Table 1.

Generally, most of the work described in the reported literature is related to grid scale power cycles, the need to use external heat sources, and only using direct expansion for the cryogenic power recovery cycle, which in general limits the advantages of these cycles. To the best of the authors' knowledge, it is only Du and Ding (2016) who is investigated the feasibility of a small-scale (lab scale) cryogenic energy storage system with a power capacity of 5 kW and total electricity storage capacity of approximately 10 kWh. Their experimental results showed that the efficiency of the small-scale cryogenic energy storage system using the large engine for generation can reach up to 44%. Therefore, this work develops a thermodynamic modeling of a novel power cycle for a micro-grid application that integrates air liquefaction plant, heat and cold storage, cryogen storage and a power recovery system, which combines direct expansion with a closed Rankine cycles, for two cryogens Lair and LN2. In this proposed cycle, the heat rejected from the liquefaction process will be stored and then used as an input to the power recovery subsystem to improve the efficiency. Also, cold is released by the power recovery subsystem, stored, and then used as an input to the liquefaction process to improve its efficiency.

To address this issue two schemes for cryogenic energy storage power plant suitable for a micro-grid system in the large residential building are proposed. The first scheme upgrades the existing

Table 1
Reported literature for combined cryogen cycles.

Author	Working fluid	Cycle arrangement	Results
Feifei and Zhang (2008)	Liquid Natural Gas LNG, nitrogen, water ammonia	two schemes combining an open expansion with Brayton cycle and Rankine cycle	the thermal efficiency of scheme 1 is 60.94%, for scheme 2 is 60%
Guizzi et al. (2015)	LAir, propane, methane,essotherm650	stand-alone air liquefaction and power recovery plant	the thermal efficiency of around (50–60%)
Li et al. (2012)	water, nitrogen, methane, Thermal-oil 66	integrated solar-cryogen hybrid power system	Integrated system can increase the power by 30% compared to the two (solar and cryogen) systems acting separately
Chino and Araki (2000)	LAir, flue gas	combines a gas turbine cycle with a liquid air storage system	Energy storage efficiency reaches 74%
Li et al. (2013)	LAir, flue gas, nitrogen, oxygen, helium	combines a gas turbine cycle with a liquid nitrogen storage system and CO_2 captured as dry ice	the thermal efficiency reaches 70%
Kantharaj et al. (2015)	LAir	Integrated Liquid Air Energy Store (LAES) with (CAES)	the thermal efficiency reaches 67%
Li et al. (2014)	Steam, LAir	integration of nuclear power generation and a CES subsystem	the thermal efficiency reaches 71.2%
Li et al. (2011)	nitrogen, LNG, LAir, flue gas	combining an open expansion, Brayton cycle	thermal efficiency reaches 64%
Morgan et al. (2015)	LAir	stand-alone air liquefaction and power recovery plant	thermal efficiency reaches 60%
Smith (1977)	LAir, water, Freon	Cryo-storage power plant	the thermal efficiency reaches 72%
Ordonez (2000)	nitrogen	closed Brayton cycle,	specific energy reaches 482 kJ/kg
García et al. (2015)	LNG, argon, methane	combining an open expansion, Rankine cycle	Exergy efficiency reaches to 85.60%
Ahmad et al. (2017)	nitrogen, xenon	combining an open expansion, Rankine cycle	the recovery efficiency of 78%